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ICT diffusion, E-governance, and sustainability in the digital era

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ABSTRACT

This study analyses the impact of information and communications technology (ICT) diffusion and e-governance on sustainability in 148 Belt and Road Initiative (BRI) partner countries. It considers control variables such as institutional quality, urbanization, research and development (R&D), and the COVID-19 effect as dummy variables. Two step-generalised method of moments analysis of a panel dataset of 148 BRI partner countries from 2013 to 2021 reveals that ICT diffusion and e-governance benefit sustainability, with R&D and institutional quality also making positive contributions, while urbanization and the pandemic negatively impact sustainability. The findings were validated through D-K regression checks and support the technology spill-over effect, innovation, triple bottom line, endogenous growth, and stakeholder theories. They highlight the significance of investing in ICT infrastructure and digital literacy programs, improving institutional reforms and governance practices, putting sustainable urban planning into practice, and supporting R&D projects to advance sustainability in BRI partner nations. This study clarifies the potential problems brought forth by the pandemic and makes suggestions for reducing its negative effects on sustainability. It contributes to evidence-based decision-making, guiding sustainable practices in BRI partner nations.

1. Introduction

The worldwide transition from resource-based economic growth to sustainable development relies on new models that can integrate economic [1], social, and ecological goals [2]. This process is closely linked to sustainability. Sustainability is the capacity to be maintained at a consistent rate or level over time [3], and involves economic, social, and environmental factors [4]. To protect the planet for future generations, the United Nations approved the 2030 Agenda for Sustainable Development in 1996 at the Earth Summit, where members agreed to achieve 17 Sustainable Development Goals (SDGs) with 169 targets by 2030. Governments are anticipated to contribute to achieving the SDGs, together with other players, businesses, and international organisations. Other than SDG 16 (Peace, Justice, and Strong Institutions), which only concerns the government, the role of the government in accomplishing other SDGs is essential and requires further investigation [5]. Many SDGs are expected to be achieved using this technology [6]. Science, technology, and innovation are linked to 48 of the 169 SDG targets, and technology can influence many other SDG targets as well [7]. Innovation theory explains how investments in research and development (R&D) and technology breakthroughs help the diffusion of information and communications technology (ICT), improve e-governance efficacy, and promote sustainable development. This is because innovation theory is concerned with the drivers and impacts of technological advancement [8].

Gavkalova et al. [9] emphasize that achieving the SDGs requires consolidation of and efficient communication between corporations, government, and society [10,11]. Collaboration among all involved parties is crucial for executing innovative solutions and utilising ICT to tackle complicated economic, societal, and environmental issues. ICT and innovation are linked to several themes and concepts across various fields. The rapid advancement of nations worldwide necessitates a dynamic shift in their economies. The nation's economic well-being, relationships, and resources are supported by ICT infrastructure, which makes it the cornerstone of sustainable development [12].

The world is changing because of improvements in ICT. Technological development is a major factor in improving living standards and wages. It also opens new channels of communication, ushers in a global

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information society, promotes economic expansion, raises educational standards, eases the process of supporting the healthcare industry, and generates additional job opportunities. Technological advancements contribute to global transformation and accelerate the pace of economic expansion [13], an effect best explained by the technology spillover effect theory, which states that technological advances in one area or region might spread to benefit other sectors or areas [8].

The diffusion of ICT is clearly crucial in the modern digital era. ICT includes technologies and tools that enable the acquisition, processing, storage, and dissemination of information. It encompasses various digital technologies, such as computers, smartphones, the Internet, software applications, and telecommunications infrastructure. ICT diffusion drives the 'dematerialisation effect', which causes societies to transition from delivering physical products to delivering services. For instance, the Internet and telephones are playing vital roles in replacing paper and physical communication through online interactions [14].

ICT reduces communication costs associated with CO_2 emissions, minimising the problem of unequal knowledge related to environmental protection [15]. From a financial perspective, it can be used for sustainable human development. ICT adoption can stimulate economic growth by boosting productivity and reducing transaction costs [16]. Chien et al. [17] claim that it has the potential to accelerate financial development, leading to good economic growth externalities [18,19]. The basis for sustainable economic development is laid by the distinct ICT pattern prevalent in developed nations. ICT is a crucial tool for accelerating a country's economic development [20]. Hence, ICT adoption may accelerate globalisation by enhancing economies of scale and promoting economic sustainability [21,22]. However, without economic transformation, ICT can harm economic growth [19]. In addition, ICT advancement promotes economic and environmental sustainability [19,23]. However, increased environmental degradation has detrimental effects on overall well-being [24] as well as health outcomes [25], inclusive development [21], inequality [26], and developmental hindrance.

The diffusion of ICT has significantly transformed governance processes through e-governance initiatives. ICT integration within governmental and institutional structures can also be used to implement e-governance, government systems, and a green economy to reach sustainability levels. ICT diffusion enhances government efficiency and transparency by enabling the digitisation of public services, e-governance initiatives, and open data policies. This streamlines administrative processes, reduces bureaucracy, and enhances citizen engagement. ICT also enables governments to provide better public services, improve decision making, and combat corruption. E-governance is a constructive institutional governance that addresses the socioeconomic and ecological challenges faced by the contemporary global economy [27,28].

The term 'e-governance' refers to the utilization of information technology in governmental operations to improve the provision of public services to citizens, other users of governmental services, and persons and organisations. The advancement of e-governance is essential for streamlining government operations, propelling national growth, and influencing sustainability on all fronts, including environmental, economic, and social [29]. Thus, e-governance is when ICT is used to integrate processes, communicate effectively, share information, disseminate policies to stakeholders, collect feedback, and improve government organisation accountability [30]. The effectiveness of governance is a critical factor in a government's ability to generate inclusive growth. An e-governance framework outlines the duties, authority, and role of organisations within the government's digital presence, including media, websites, and other online goods and services [31].

In Western countries, e-governance programs are implemented to ensure the electronic dissemination of information and the provision of services through the Internet or other digital channels [32]. E-governance is the application of electronic means of streamlining and enhancing political, governmental, and commercial governance. It constitutes the dynamic interactions between the government, the populace, and businesses; and the internal workings of the government [33,34]. According to Erkut [30], e-governance can improve human rights, encourage institutional transparency, combat corruption and nepotism, and move political decision making from analogue to digital. It currently needs help in handling the acknowledged problems in economics. While e-governance can benefit from minimising agency and transaction costs and capitalising on network externalities, each e-governance initiative must adapt its processes accordingly and recognise its inherent limitations.

In this era of contemporary governance through technology (e-government), development actors have emphasised the goal of sustainable development, especially through technical green economy [35]. Development is a comprehensive process that involves modifications and transformations, such as e-governance, and has no equilibrium state [36]. To achieve sustainability, e-governance reforms and the integration of ICTs into government services promote data abstraction and virtualisation [37]. From the perspective of e-governance transformation, governments are increasingly implementing strategies to improve online service participation and information access in least-developed nations, especially in rural areas, thereby fostering green growth that eventually contributes to sustainability [38]. Owing to the digital revolution, governments in developed and developing nations can now use ICTs to make it easier to enact integrated policies and provide public services. This encourages the development of solid and open institutions, ultimately assisting in accomplishing sustainability goals [39]. In today's globalised world, institutional quality and sustainability are intertwined. Sustainability is facilitated by reasonable governance procedures that allow domestic and international investors to freely make investment decisions [40].

This study examines the impact of ICT diffusion on Sustainability and how e-governance influences sustainability across 148 Belt and Road Initiative (BRI) partner countries. It includes institutional quality, urbanisation, and R&D as control variables, and COVID-19 as a dummy variable. This study employed cross-sectional data and measured sustainability using adjusted net savings. Although some research has been conducted on how ICT diffusion and e-governance affect sustainability, further studies are required to identify the precise mechanisms through which these factors affect sustainability outcomes. The complex interactions between ICT diffusion, e-governance, and sustainability may not be sufficiently covered by the current literature, particularly when it comes to the nations involved in the BRI.

This study adds to the current literature by presenting empirical evidence of the impact of the spread of ICT and e-governance on sustainability outcomes in 148 BRI partner countries. This study improves our understanding of the complex dynamics that influence sustainability in the digital era through thorough analysis and validation via regression checks. Recognising the factors that contribute to sustainability, both positively and negatively, and based on well-established theoretical frameworks, such as innovation theory, technology spillover effect theory, and stakeholder theory, improve theoretical discourse and guide practical actions. Furthermore, the study's use of control variables and longitudinal analysis from 2013 to 2021 add depth and nuance to the findings, providing valuable insights for policymakers, practitioners, and researchers looking to advance sustainable development agendas within and beyond the BRI context.

The remaining paper is organised as follows: Section 2 presents the literature summary and hypotheses. Section 3 describes the research methodology, descriptive statistics, and design. Section 4 presents the results and analysis. Section 5 concludes.

2. Literature review

2.1. ICT diffusion and sustainability

Increased ICT usage has diverse economic consequences for businesses, including faster economic development, financial sector breakthroughs, greater educational attainment, and improved environmental sustainability [41]. Meanwhile, academia has begun to focus on ICT adoption and sustainability. ICT has played a significant role in social, political, and sustainable economic development worldwide. Per Iqbal et al. [13], ICT diffusion has promoted sustainable economic development in the 53 BRI nations from 1990 to 2020.

Jayaprakash (2022) used supposedly unrelated regression estimation to analyse a dataset of 80 countries from 2000 to 2016 and found that ICT diffusion positively influences the environmental, economic, and social aspects of sustainability. The widespread adoption of ICT, even in isolated nations, offers hope for addressing sustainability challenges. Verma et al. [42] examined the environmental sustainability of 20 developing nations between 2005 and 2019, focusing on the effects of ICT diffusion and institutional quality on CO2 emissions. A unit increase in ICT was found to lower CO_2 emissions by 0.007 using robust CSD, such as Westerlund co-integration and system generalised method of moments, eventually increasing sustainability.

Majeed and Ayub [43] examined the effect of ICT diffusion on the development of 149 nations between 1980 and 2015. They confirm the beneficial impact of ICT on growth. Regarding the relationship between ICT diffusion and economic sustainability, their findings imply that ICT diffusion is advantageous for advancing global sustainability. Ramasubramanian et al. [44] presented a data-driven narrative exploring the impact of ICT development on economic sustainability, considering the complexities of sustainability and the diverse recommendations offered by digital technologies. Their analysis utilised a panel dataset of 39 advanced and developing nations. To conduct the study, they employed cross industry standard process for data mining, which is both adaptable and robust, and known for its practical approach to data analytics. The results highlight how high- and low-income economies have different economic sustainability outcomes and raise valid concerns about the ability of low-income economies to accomplish the SDG by 2030 through ICT intervention.

Utilising balanced panel data of 1990–2018, Saud et al. [45] explored how ICT and financial development shape a low-carbon environment for 60 BRI economies. They confirm a negative relationship between ICT use and CO_2 emissions. Thus, an increase in ICT diffusion reduces carbon emissions and contributes to sustainability. Nchofoung and Asongu [46] observed the influence of ICT diffusion on sustainability and examined the underlying mechanisms that influence this effect. Their study investigated a large dataset of 140 nations from 2000 to 2019. They used various statistical methods such as the fixed effects estimator, Driscoll and Kraay estimator, and GMM techniques to evaluate the connection between ICT diffusion and sustainability. The outcomes show a solid and favourable relationship between ICT diffusion and sustainability. We thus hypothesise—

H1. *ICT diffusion fosters the advancement of sustainability.*

2.2. E-governance and sustainability

The SDGs, which include ensuring sustainability by tackling present and future difficulties, including the long-term and potential effects of COVID-19, are at the centre of e-governance. Supporting, sustaining, and maintaining the circumstances required for a prosperous future are aspects of sustainability. E-governance is essential for advancing transformative development because it improves the standards of good governance by enhancing the efficacy, efficiency, and quality of resource management [29], which contributes to sustainability. E-governance has critical long-term effects on both political and business spheres. Consequently, there is an ongoing conflict between democratic and illiberal actors in shaping the digital economy according to their respective ideologies [47]. Contemporary patterns of digital transformation in governance encounter novel societal challenges regarding sustainability, including but not limited to climate change and the depletion of natural resources [5]. Lyulyov et al. [48] found that e-governance significantly contributes to attaining the SDGs and promoting sustainability.

Ellalee and Al-Qaysi [49] examined how e-governance might support an inclusive society and sustainable development, using a sample of 103 countries from 2003 to 2018. These findings demonstrate that e-governance increases the possibility of achieving sustainability, particularly in developing and transitioning countries. Palos-Sánchez et al. [50] examined the local government response towards COVID-19 through digital transformation and its contribution to the achievement of the SDGs in Spain. This study highlights the significance of local governments' creative initiatives in attaining SDGs, specifically SDGs 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), 10 (Reduced Inequality), and 11 (Sustainable Cities and Communities). This emphasises the need for technological security measures to enhance local government staff morale during the COVID-19 pandemic.

Abuljadail et al. [51] found that electronic communication solutions reduced the number of vehicles or logistical techniques required for communication between local governance and stakeholders, thereby increasing sustainability. Xue et al. [52] examined the impact of e-governance on the efficiency of natural resource utilisation across 153 nations; they provide insightful information for the creation of energy policies aimed at improving efficiency and advancing sustainable development. They confirm that e-governance can be highly advantageous for nations afflicted with the resource curse by providing innovative ways to break the curse and boost sustainability.

Lopes and Castro [53] assessed the influence of e-governance on sustainability by utilising a logit model and analysing data from 103 countries from 2003 to 2018. They measured sustainability by the adjusted net savings, encompassing environmental, economic, and social dimensions, and proved that e-governance increases the likelihood of attaining sustainability, particularly in developing and transitional economies. Malik and Majeed [54] examined the influence of e-governance on economic sustainability. They used ordinary least squares and instrumental variable econometric techniques to analyse the cross-sectional sample data of 147 nations from 2003 to 2012. They found that e-governance adoption contributes positively to economic sustainability. We thus hypothesise—

H2. *E-governance makes a positive and significant contribution to sustainability.*

2.3. Control factors affecting sustainability

2.3.1. Institutional quality and sustainability

A key component of the effectiveness of sustainable development is its institutional aspect. Institutional quality includes six indicators: government effectiveness, voice of accountability, regulatory quality, corruption and rule of law, and political stability. Regulatory avenues, including legal, administrative, social, environmental, commercial, and globalisation procedures, allow institutions to impact sustainability [55].

Using a panel dataset of G20 countries from 2000 to 2022, Azimi and Rahman [56] explored the impact of institutional quality on ecological footprint. Their findings show that institutional quality has a significant impact on reducing the negative effects of external shocks on the ecological footprint. Between 2002 and 2018, the ecological footprints of two sets of growing European and Asian countries were assessed for their implications on informality, institutional quality, and renewable energy use [57]. The findings are consistent with a thorough understanding of the value of informality and institutional quality in simultaneously reducing social and environmental threats.

Li et al. [58] investigated how institutional quality in G7 economies had an asymmetric impact on environmental sustainability from 1986 to 2020. Higher institutional quality lowers CO_2 emissions and boosts environmental sustainability; they also found an inverse link between institutional quality and CO_2 emissions. Hunjra, Azam, et al. [55] looks at how institutional quality affects sustainable development in 65 emerging economies for the period between 1984 to 2019. These findings indicate that institutional quality has a beneficial effect on economic sustainability. Regarding the environment, they found the institutional ineffectiveness of deforestation, while a negative association between institutional quality and CO_2 emissions throughout the areas, indicating contributions to environmental sustainability.

Regarding the influence of institutional quality on sustainable development, system GMM and fixed effects analysis of panel data of 66 developing nations from 1984 to 2019 reveals that institutional quality contributes positively to sustainable development [59]. In particular, lower-middle-income countries benefit more from institutional quality contributions to sustainable development than low-income nations. We thus hypothesise—

H3. *Institutional quality (governance) positively and significantly influences sustainability.*

2.3.2. Urbanisation and sustainability

Kwilinski et al. [60] investigated the impact of urbanisation on the sustainable growth of European countries from 2005 to 2020. Their results demonstrate that urbanisation negatively influences sustainable growth. Yang et al. [61] empirically investigated the influence of urbanisation on carbon emission efficiency in Western China from 2010 to 2019. They found that urbanisation negatively influences carbon emission efficiency, indicating that urbanisation harms environmental sustainability.

Dogan and Turkekul [62] explored the influence of urbanisation on carbon emissions in the United States. Based on autoregressive distributed lag analysis covering 50 years, they discovered a direct association between trade openness and environmental quality and an indirect correlation between energy use and urbanisation. Further, the environment Kuznets curve does not exist in the United States when compared with 80 countries from 1983 to 2005 using fixed random approaches. Ponce de Leon Barido and Marshall [63] observed that urbanisation negatively affects the climate: a 1% increase in the urban population would cause a 0.95% increase in atmospheric CO_2 emissions, which would eventually reduce environmental sustainability.

Mehmood and Mansoor [64] found that urbanisation has dramatically reduced environmental degradation and increased environmental sustainability in China, Mongolia, Hong Kong, and Japan. Urbanisation has also caused environmental degradation in Singapore, South Korea, and Macao, reducing environmental sustainability. Their study has policy implications for Singapore, South Korea, and Macao when considering urbanisation strategies. Adams et al. [65] claimed that urbanisation negatively influences environmental sustainability. Ali et al. [66] observed that urbanisation negatively affects environmental sustainability by increasing carbon emissions in Pakistan. In select countries, Anwar et al. [67] observed that urbanisation, economic development, and trade openness significantly impacted environmental sustainability. Consequently, the primary policy recommendation is to promote environmentally friendly and sustainable urbanisation that aids economic sustainability without endangering the environment. We thus hypothesise—

H4. *Urbanisation negatively and significantly influences sustainability.*

2.3.3. R&D and sustainability

Can R&D help with sustainability and the accomplishment of the SDGs [68]. Building research capability in underdeveloped nations may aid in the pursuit of sustainability [68,69]. Indeed, investing in R&D can help measure the advancements that lead to economic sustainability [70]. R&D refers to the original, scientific effort done to advance the boundaries of knowledge, including 'man knowledge, social understanding, and culture', and leveraging this body of knowledge to create novel items or boost production and efficacy [70].

Olaoye (2021) revealed that R&D and governance contribute significantly to economic sustainability in their target African nations; they recommend African countries to increase their R&D investments and ensure effective governance to achieve economic sustainability. According to Li and Ullah [71], R&D intensity helps Asian nations switch to sustainable energy sources, ultimately increasing their sustainability. Per Alola et al. [72], R&D expenditures in the renewable energy sector play a significant role in the notable rise in technologies that contribute to sustainability in the 12 countries they targeted. For the period of 1990–2011, Ozcan and Ari [73] examined the association between R&D and economic sustainability in OECD nations. Their discoveries revealed that R&D has a beneficial influence on economic sustainability. To evaluate the connection between R&D and economic sustainability, Genc and Atasoy [74] employed annual data from 1997 to 2008 for 34 nations. Their results show a direct causal connection between R&D and economic sustainability. R&D also positively contributes to environmental sustainability [75]. We thus hypothesise—

H5. *R&D significantly and positively affects sustainability.*

2.3.4. COVID-19 and sustainability

The COVID-19 pandemic—a major health and developmental problem—has negatively affected the world, jeopardising numerous aspects of society. To protect populations from the disease, governments worldwide have implemented safeguards such as lockdowns, shelter-in-place orders, social exclusion, and constrained foreign travel.

All nations are facing developmental challenges that arose from COVID-19 [76,77]. To varying degrees, the pandemic has negatively affected progress toward the 2030 Vision for SDGs [78]. Early literature on the effects in 2020 offered conventional opinions or observations on COVID-19 and sustainability. For instance, Filho et al. (2020) conducted a thorough analysis of COVID-19 on the SDGs. Later, Ranjbari et al. [79] focused on developing domain knowledge through a systematic review. We thus hypothesise—

H6. *COVID-19 has a statistically significant and negative effect on sustainability.*

2.4. Theoretical and conceptual framework

This study offers a comprehensive framework for understanding the intricate interactions and effects of digital initiatives on sustainable development by integrating theoretical perspectives with the variables ICT diffusion, e-governance, sustainability, institutional quality, urbanisation, R&D, and the COVID-19 dummy variable. Fig. 1 demonstrates the conceptual model used herein.

According to the technology spillover effect theory, technological advances in one area or region may spread to benefit other sectors or locations [8]. Technology spillovers can occur in the setting of the study variables through ICT diffusion and innovation, resulting in better e-governance practices, long-term development effects, and institutional capacity building. For example, ICT innovations can spread from cities to rural areas, improve service access and support economic growth. Innovation theory is concerned with the drivers and impacts of technological advancement [8]. In this study's setting, innovation theory helps explain how investments in R&D and technological breakthroughs help spread ICT, improve e-governance efficacy, and promote sustainable development. Innovation in digital technology can result in new e-governance solutions, sustainability practices, and economic models that address societal requirements and issues.

The triple bottom line theory evaluates the performance of societies or organizations in terms of the social, economic, and environmental aspects [80]. This theory helps assess the effects of ICT diffusion, e-governance, and other factors on social justice, economic growth, and environmental sustainability when applied to the study variables. E-governance projects can enhance social openness and accountability,

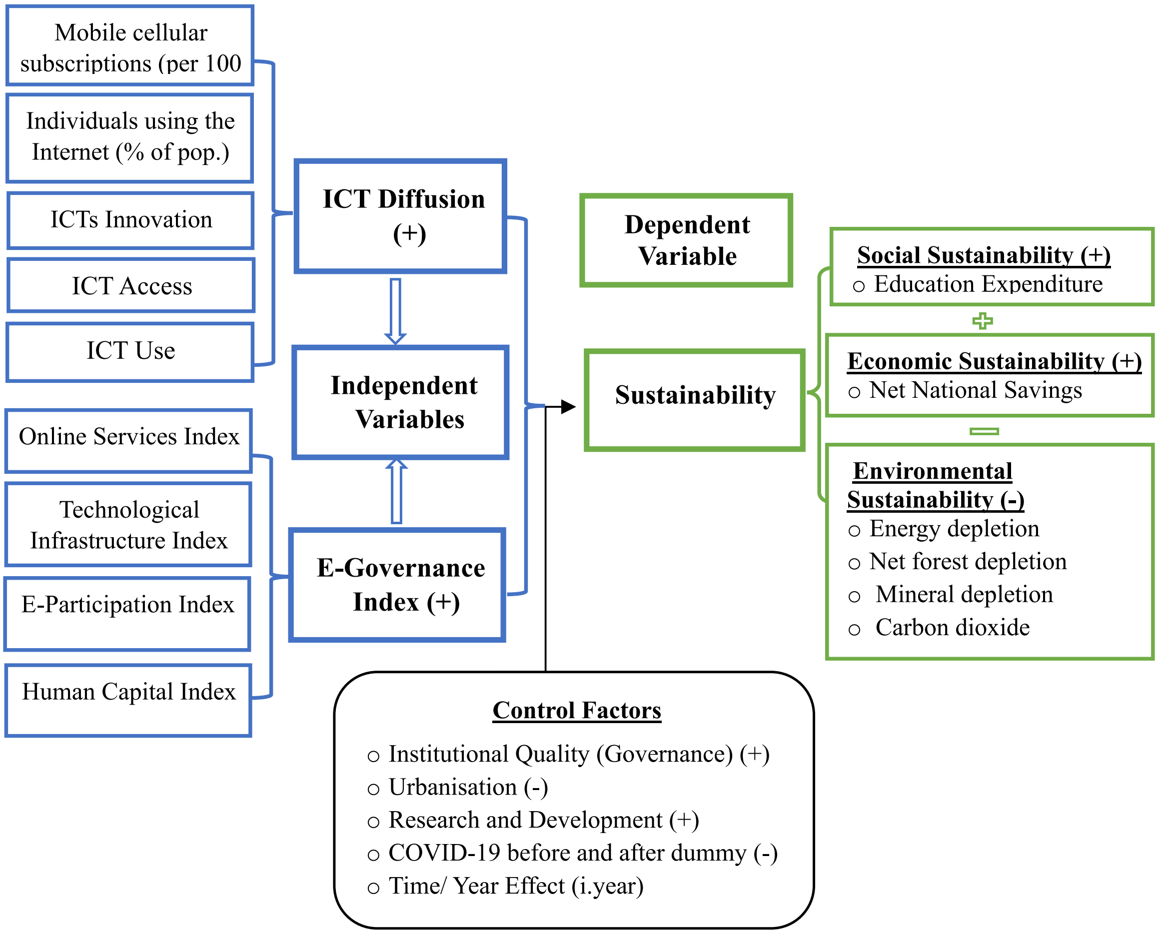

Figure 1. Conceptual model

maximise environmental resource utilisation, and boost economic output. Endogenous theory focuses on how internal elements, such as institutions and human capital, propel economic growth and advancement in technology [81]. Within the framework of this study, endogenous variables such as human capital and institutional quality impact the diffusion of ICT, efficacy of e-governance, and sustainability outcomes. Robust institutions have the potential to cultivate an atmosphere conducive to innovation and sustainable growth, and educational and skill-building initiatives can augment a society's ability to adopt novel technologies.

Stakeholder theory emphasises recognising stakeholder interests and viewpoints in decision making [82]. The stakeholder theory shows how governments, corporations, civil society organisations, and individuals are involved in ICT diffusion, e-governance, and sustainable development. Stakeholder involvement in digital project design and implementation improves its efficacy and legitimacy, leading to sustainable development. The COVID-19 pandemic has accelerated digital transformation and highlighted the importance of ICT solutions in solving global problems. The COVID-19 dummy variable measured the influence of the pandemic on ICT diffusion, e-governance, and sustainability, thus emphasising the necessity for active and resilient digital techniques to alleviate socioeconomic catastrophes and improve rebuilding.

This study better comprehends ICT diffusion, e-governance, and sustainability by integrating these theoretical viewpoints with the study factors. This interdisciplinary approach can inform digital technology policies, investments, and governance frameworks for equitable and sustainable development.

2.4.1. *Conceptual framework*

3. Methodology

3.1. *Data and measurement*

This study explores the dynamic influence of ICT diffusion and e-governance on sustainability in BRI partner countries. It considers institutional quality (measured by six indicators), urbanisation, R&D, and the COVID-19 effect as a dummy variable as control variables. The analysis utilises longitudinal panel data from 148 BRI partner countries covering 2013 to 2021, based on the best available panel data. Sustainability has many facets and is complex, which has led to the development of various indices. However, some of these metrics do not fully account for all aspects of sustainability [83].

The World Bank's adjusted net savings are just one of many sustainability indicators mentioned in the literature; however, they have gained widespread prominence [84–90]. The dependent variable was the sustainability index based on social, environmental, and economic dimensions using adjusted net savings, and the independent variables were ICT diffusion and e-governance. The control variables were urbanisation (urban population growth annual %), R&D expenditure expressed as a percentage of GDP), and the COVID-19 effect (dummy variable of zero from 2013 to 2018 while one since COVID-19 from 2019 to 2021). The details of these variables are listed in Table 3.1.

Table 3.1
Measure of the Dependent, Independent, and Control Variable

Variable	Variable Details	Data Source
Sustainability Index	Based on Adjusted net savings, accounting for damage from particle emissions (as a percentage of GNI).	World Bank
ICT Diffusion (PCA index)	The PCA index evaluates mobile cellular subscriptions, Internet usage, ICTs, ICT access, and ICT use during the COVID-19 pandemic, which has led to slower productivity growth and other new difficulties, is the background for the Global Innovation Index (GII), which tracks current global innovation trends	World Bank; Global Innovation Index (GII)
E-governance Index (EGI PCA Index)	The EGI is a composite metric that considers the e-governance factors as an e-participation index, online service provision, and telecommunication connection, as well as other important aspects of e-government.	U.N. (United Nations)
Institutional Quality (Governance-WGI)	PCA index of (1) government effectiveness, (2) corruption control, (3) voice and accountability, (4) rule of law, (5) political stability and absence of violence, and (6) regulatory quality.	World Bank (WDI)
Urbanisation	Urban population growth (annual %) is computed using data from the World Bank and United Nations World Urbanisation Prospects.	World Bank (WDI)
Research and Development	R&D expenditure as % of GDP.	World Bank (WDI)
COVID-19 Effect	Dummy variables of 1 and 0. Zero from 2013 to 2018, while 1 since COVID-19 from 2019 to 2021.	Author

3.2. Methods

This study employed the following two-step system: GMM for a dataset spanning nine years (2013–2021) across 148 BRI partner countries. The objective of this study was to analyse the effect of ICT diffusion and e-governance on sustainability. The study also included control variables, such as institutional quality, urbanisation, R&D, and the COVID-19 effect as dummy variables. The GMM is a suitable approach for analysing panel datasets in this study, as it satisfies the requirement of having more cross-sections (N) than periods (T). The two-step GMM effectively addresses overidentifying constraints, measurement errors, endogeneity biases, and autocorrelation issues. However, this approach did not consider panel heterogeneity. The three-panel regressions were confirmed to use a fixed-effects model using the Wald test, commonly known as the Hausman test, which detects panel heterogeneity. As a result, the GMM was used in this study to estimate the dynamic model. This method is particularly effective when the distribution of the dependent variables is undifferentiated. The dynamic model is expressed as follows:

$$SI_{it} = \beta_0 + \beta_1 SI_{it-1} + \beta_2 ICTD_{it} + \beta_3 EGOV_{it} + \beta_4 IQ_{it} + \beta_5 UBN_{it} + \beta_6 RD_{it} + \beta_7 Covid\_19_{it} + \vartheta_t + \epsilon_{it} \tag{1}$$

Here, SI_{it} represents the sustainability index i (i=1,2,3…..N) denotes the country and time is represented by t (t=1,2,3…. T), and SI_{it-1} represents the time-lagged value of the dependent variable. Furthermore, *ICTD*, *EGOV*, *IQ*, *UBN*, *RD* and $Covid_{19}$*dummy* variable signifies ICT diffusion, e-governance, institutional quality (governance), urbanisation, and R&D, respectively. In addition, ϵ_{it} denote error term and ϑ_t represents the time effect. β's indicates unknown parameters to be estimated.

The unit root test for the CIPS was utilised, and a robustness check was conducted using the Driscoll and Kraay (D-K) fixed-effect standard error method. This method addresses cross-sectional, heteroscedastic, spatial, and serial dependencies. It is effective for handling various forms of panel data and unbalanced values.

4. Results and discussion

4.1. Analysis results and interpretation

Table 1 presents the descriptive statistics of the selected variables. The dataset consists of 1332 observations from 148 BRI partner countries. Measures of central tendency, such as the mean and median, and markers of data variability, such as the standard deviation and maximum values, were included in the descriptive analysis. These statistics confirm the reliability of the data and provide an overview of the sample. The presence of varying values indicates the average level of dispersion within the sample. Table 1 displays negative values. For example, Sustainability measured at -0.741, which signifies that the observed data point is lower below the mean for that specific characteristic. Negative values signify values that fall below the averages of the corresponding variables. These values provide information on the distribution and features of the analysed data.

Table 2 shows the pairwise correlations among the dependent, independent, and control variables. The findings revealed positive correlations between all variables and sustainability (SI) variables at a significance level of 1%, except for urbanisation and COVID-19, which demonstrated negative correlations with SI at significance levels of 1% and 5%, respectively. These findings strongly support the hypotheses, as the independent and control variables show significant correlations with the dependent variable.

In Table 3, the outcomes of the multicollinearity analyses reveal the variance inflation factor (VIF) scores and the reciprocal of the VIF (1/VIF) values. VIF scores below 5 and 1/VIF values greater than 0.5 show the absence of multicollinearity in the data.

Table 4 displays the findings of the second-generation unit root tests for the CIPS. The table shows the variables at two different levels: 'At Level' and 'First Difference'. sustainability is stationary in its original form (At Level) with a 5% significance level. ICT diffusion is stationary in the first difference with a 5% significance level. E-governance is stationary in its original form (At Level) with a 1% significance level. Institutional quality and urbanisation were stationary at the first difference, with a 1% significance level. R&D and COVID-19 dummies are stationary in their original form (At Level) with a 1% significance level. All variables exhibit both stationarity and statistical significance, leading to acceptance of the alternative hypothesis (Ha). This indicates that the dynamic nature model is suitable for analysis, and further strengthens the validity of the model's results.

Table 5 demonstrates the outcomes of the cointegration estimations using the Westerlund [91], Pedroni [92], and Kao [93] tests to confirm the cointegration of the model panels. These tests indicate the presence of a co-integrated panel. The results supported the alternative hypothesis (Ha). The Westerlund test, the most recent and advanced method for checking panel dataset cointegration, revealed statistically significant cointegration, with a test statistic value of -4.556 at the 1% significance level. Consequently, the null hypothesis (H0) of no cointegration was

Table 1
Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max
Sustainability	1332	.978	.731	-.741	2.559
ICT Diffusion	1332	-.056	.469	-.234	3.364
E-governance Index	1332	1.590	.571	-.689	2.347
Institutional Quality (Gov. Index)	1332	0.000	1.000	-1.519	1.654
Urbanisation	1332	.003	.989	-2.919	1.761
R&D	1332	1.601	.571	-.688	2.349
COVID-19 (Dummy)	1332	0.500	0.500	0.000	1.000

Table 2
Pairwise correlations

Sr	Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1)	SI	1.000					
(2)	ICTD	0.291***	1.000				
(3)	EGI	0.235***	0.214***	1.000			
(4)	Institutional Quality (Gov. Index)	0.319***	0.351***	0.410***	1.000		
(5)	Urbanisation	-0.091***	-0.125***	-0.064	0.110***	1.000	
(6)	RND	0.127***	0.163***	0.234***	-0.093**	0.224***	1.000
(7)	COVID-19 Dummy	-0.265**	-0.168***	-0.464	0.093	-0.350**	1.000

Table 3
Variance Inflation Factor with Time Effect

Variables	VIF with Time effect (1-2)	
	VIF	1/VIF
Sustainability	1.529	.648
ICT Diffusion	1.374	.719
E-governance Index	1.285	.766
Institutional Quality (Gov. Index)	2.398	.421
Urbanisation	1.536	.637
R&D	2.379	0.370
COVID-19 Dummy	0.010	0.003
i.year effect	YES	YES
Mean VIF	**1.969**	**.**

Table 4
Results of Second-Generation Unit Root for CIPS

Variables	At Level	First Difference
Sustainability Index	-2.605**	-
ICT Diffusion	-1.894	-2.453**
E-governance Index	-2.668***	-
Institutional Quality (Gov. Index)	-3.424	3.045***
Urbanisation	-2.864	-3.756***
R&D	-2.537***	-
COVID-19 Dummy	−1.436***	

Standard errors are in parentheses: *** p<0.01 (1%), ** p<0.05 (5%), * p<0.1 (10%)

Table 5
Tests for the Cointegration

Detail	Value	Accepted/Rejected
Westerlund test for cointegration		
Variance ratio	-4.556***	Ha: All panels are cointegrated (Accepted)
No. of panels: 148		
Avg. no. of periods: 9		
Cointegrating vector: Panel specific		
Panel means: Included		
Time trend: Included		
AR parameter: Same		
Cross-sectional means removed		
Pedroni test for cointegration		
Modified Phillips-Perron t	3.4357***	Ha: All panels are cointegrated
Phillips-Perron t	-22.5678***	(Accepted)
Augmented Dickey-Fuller t	-19.8664***	
No. of panels =148	Cointegrating vector: Panel specific	
Panel means: Included	Kernel: Bartlett	
Avg. no. of periods = 9	Time trend: Included	
Augmented lags: 1	Lags: 2.00 (Newey-West)	
Cross-sectional means removed	A.R. parameter: Panel specific	

Standard errors are in parentheses: *** p<0.01 (1%), ** p<0.05 (5%), * p<0.1 (10%)

rejected. The results are summarised in Table 5.

The estimation outcomes of sustainability (SI) are presented in Table 6 using the dynamic final model, which incorporates the two-step system GMM and includes robustness checks using the D-K regression models. The final model, shown in column (1), is determined based on the Wald test results and the criteria set for the two-step system GMM estimation. The findings of various diagnostic tests for the corresponding model are presented in column (1) of Table 6. These tests assess the fulfilment of the necessary assumptions for the model residuals, ensuring accurate inference and confirmation of outcomes. Thus, the p value of the first-order autocorrelation (AR1) is not higher than 5%, confirming the absence of a serial correlation. The first-order differences in the tested model variables did not show any autocorrelation. Furthermore, the p value of the second-order autocorrelation (AR2) exceeded 5%, suggesting that system GMM is a suitable estimation method for this sample, given the total count. (N = 148) exceeds the number of periods (T = 9). Within the Wald–Chi square test model, all included variables were found to be significant.

The Wald test, Chi square test, and F-statistics all yield p values of 1%, suggesting that the model presented in column (1) is suitable for analysis. The Hansen statistic yielded a value of 78.32 with a corresponding p value of 0.187, whereas the Sargan statistic was as 347.8 with a p value of 0.145. The Hansen and Sargan tests indicate that, while

Table 6
Results of Two-Step System GMM and Robust D-K standard error Fixed Effect Regression

Dep. Variable	(1) Two-step Sys-GMM Main Model	(2) D-K F.E. Regression Robust Model
Sustainability Index (1-t)	0.578***	
	(0.028)	
ICT Diffusion	0.075**	0.129*
	(0.043)	(0.035)
E-governance Index	0.135***	0.118**
	(0.038)	(0.025)
Institutional Quality (Gov. Index)	0.182***	0.210***
	(0.031)	(0.061)
Urbanisation	-0.045*	-0.063**
	(0.011)	(0.013)
R&D	0.093**	0.087*
	(0.023)	(0.021)
COVID-19 Dummy	-0.202**	-0.234**
	(0.095)	(0.110)
i.year effect	Yes	Yes
Observations	1184	1332
AR1	-6.342	
A11 p value	0.002	
AR2	5.644	
AR2 p value	0.345	
Sargan	347.8	
Sargan P value	0.145	
Hansen	78.32	
Hansen p value	0.187	
Chi2/Wald test	2345	
Chi2 p value	0.0000	
J-stat, Instruments	15	
within R-squared		0.6578
Prob > F		0.0000
No. of Countries	148	148

Standard errors are in parentheses: *** p<0.01 (1%), ** p<0.05 (5%), * p<0.1 (10%)

there may be an excessive identification of constraints, it enhances the reliability of instruments and evidence that contradicts the null hypothesis. Column (1) demonstrates that sustainability has a positive lag coefficient of 0.578 with a 1% significance level. Independent variables, such as ICT Diffusion, have a positive value of 0.075 with a 5% significance level, and e-governance has a positive value of 0.135 with a 1% significance level.

These results reveal that the independent variables (i.e., ICT diffusion and e-governance) positively contribute towards the sustainability of the BRI 148 partner countries. In addition, control variables such as institutional quality and R&D have a positive 0.182 value with a 1% significance level and a 0.093 value with a 5% significance level, respectively. At the same time, the urbanization and COVID-19 dummy variables have negative values (-0.045) at the 10% level and (-0.202) at the 5% significance level. The findings of the control variables show that institutional quality, R&D positively contribute to sustainability, whereas urbanization and COVID-19 hinder sustainability. In conclusion, the analytical test results confirmed the fulfilment of all the required assessment assumptions, highlighting the precision and coherence of the employed methodology, as shown in Table 6.

Column (2) of Table 6 reveals the robust model results using the D-K fixed effect regression. ICT diffusion is the independent variable with a positive value of 0.129 and a 10% significance level comparable to the primary model. E-governance also had a positive value of 0.118 at the 5% significance level, comparable to the primary model. For the control variables, institutional quality has a positive value of 0.210 at the 1% significance level, which is comparable to the primary model. R&D also has a positive value of 0.087, with a 10% significance level, comparable to the primary model. Simultaneously, urbanization and COVID-19 had negative (-0.063) and (-0.234) values, respectively, with a 5% significance level comparable to the primary model. T

The D-K regression results confirmed the outcomes of the primary model using the two-step system GMM. The D-K regression analysis confirmed the absence of cross-sectional dependence issues such as endogeneity in the main model. This endorsement supports the use of the final model employing the two-step system GMM, which is considered effective and suitable as a case of ordinary least square, fixed effects, and two-stage least square estimation methods.

4.2. Discussion

ICT diffusion is approximately H1 and positively influences sustainability. Therefore, the null hypothesis is rejected in favour of the alternative hypothesis, H1. This promotes sustainability in the BRI's 148 partner countries. According to innovation and technology spillover effect theories, ICT diffusion improves sustainability through knowledge transfer and cross-sectoral innovation. ICT can promote sustainability in the 148 BRI partner nations by combining the stakeholder theory and the sustainability triple bottom-line framework. These results are supported by Iqbal et al. [13], who demonstrated that the utilisation of Information and Communication Technology (ICT) diffusion promoted sustainable economic development in 53 BRI nations from 1990 to 2020. These outcomes also align with those of Saud et al. [45], who find a negative relationship between ICT and CO_2 emissions. This means that an increase in ICT diffusion reduced carbon emissions which contributed to the environmental sustainability 60 Belt and of the (BRI) economies from 1990 to 2018. These findings are consistent with those reported by Nchofoung and Asongu [46]. They found that ICT diffusion has a positive relationship with sustainability by focusing on datasets from 140 countries spanning 2000 to 2019. The data were analysed using GMM.

For H2, we accept the alternate hypothesis and reject the null hypothesis because e-governance also positively influences sustainability in the BRI 148 partner countries. The alternative hypothesis for H2 supports stakeholder and endogenous theories, showing that e-governance improves institutional quality and stakeholder participation, and boosts sustainability. E-governance efforts have socioeconomic and environmental benefits that support the sustainability triple-bottom-line paradigm. The outcomes also align with those of Ellalee and Al-Qaysi [49], who found that e-governance increases the possibility of attaining sustainability, particularly in developing and transitioning nations, using a sample of 103 countries from 2003 to 2018. These findings are supported by Lyulyov et al. [48], who found that e-governance significantly contributed to attaining the SDGs and promoting sustainability. This outcome is consistent with Lopes and Castro [53], who found that e-government development positively contributed to a country's ability to achieve sustainability by employing a dataset of 103 nations from 2003 to 2018.

Moreover, H3 concerns institutional quality, so the null hypothesis is rejected, and we accept the alternate hypothesis because it has a favourable influence on sustainability in the BRI 148 partner countries. The null hypothesis for H3 is rejected, supporting the endogenous and stakeholder theories that institutional quality improves sustainability through effective governance and stakeholder involvement. The sustainability triple bottom-line concept emphasises strong institutions for economic, social, and environmental sustainability. This contributes to sustainability by strengthening institutional quality and good governance. These outcomes are supported by Azimi and Rahman [56], who observed that institutional quality has a significant impact on reducing the negative effects of external shocks on ecological footprints using a panel dataset of G20 countries from 2000 to 2022. These findings align with those of Hunjra et al. [55], who found that institutional quality had a beneficial impact on sustainability in 65 emerging economies from 1984 to 2019.

Regarding H4, the null hypothesis is rejected and we accept the alternate hypothesis because urbanisation negatively impacts sustainability in the BRI 148 partner countries. Rejecting the null hypothesis for H4 supports the technological spillover effect theory and sustainability triple bottom-line paradigm, implying that rapid urbanisation can harm the environment and society, thus complicating sustainability efforts. Integrated urban planning and governance based on stakeholder and innovation theories is required. These findings align with those of Kwilinski et al. [60], who demonstrated that urbanisation negatively influenced the sustainable growth of European countries from 2005 to 2020. These outcomes are consistent with those of Yang et al. [61], who found that urbanisation harms environmental sustainability in Western China from 2010 to 2019.

H5 is related to R&D. We accept the alternate hypothesis because it positively influences sustainability in the BRI 148 partner countries and reject the null hypothesis. The innovation theory and technology spillover effect theory support the alternate hypothesis for H5, which suggests that R&D spending boosts sustainability by fostering technological innovation and knowledge transfer. According to stakeholder theory and the sustainability triple bottom-line paradigm, R&D is crucial for solving global problems and promoting sustainable development. These outcomes align with Olaoye's (2021) study, which found that expanding R&D capabilities can positively contribute to Africa's sustainability. These findings also align with [75] who found that R&D positively contributes to sustainability.

While H6 deals with COVID-19, the null hypothesis is rejected, and we accept the alternate hypothesis because it affects sustainability in the BRI 148 partner countries. Rejecting the null hypothesis for H6 supports the stakeholder theory and technological spillover effect theory, showing that the COVID-19 pandemic has disrupted economic activity and worsened social and environmental issues. This shows how global crises are interconnected and the necessity for resilient, adaptive methods based on innovation theory and the sustainability triple bottom-line framework. The outcomes align with Ekwebelem et al.'s [78] study, which found that COVID-19 adversely impacted advancement towards the 2030 Vision for Sustainable SDG's and Sustainability. These outcomes align with [76,77]. They observed that all nations now face difficulties growing because of the COVID-19 escalation of to a global calamity.

5. Conclusion

The current study analyses the influence of ICT diffusion and e-governance on sustainability, institutional quality, urbanisation, and R&D as control variables and the COVID-19 effect as a dummy variable in 148 partner countries of the BRI using the two-step GMM method. Moreover, the D-K fixed-effects standard error method was used as an alternative approach to ensure additional robustness. The two-step GMM results reveal that ICT diffusion positively affects sustainability, promoting sustainability in the 148 BRI partner countries. E-governance positively influences sustainability. Institutional quality has a favourable impact on sustainability. This contributes to sustainability by strengthening institutional quality and good governance. Urbanisation hampers sustainability. Simultaneously, R&D positively influences sustainability, while COVID-19 damages it. In contrast, the D-K regression results validated the GMM results. Based on these findings, the alternate and null hypotheses are rejected for all variables.

This study improves our understanding of the complex dynamics that influence sustainability in the digital era through thorough analysis and validation via regression checks. Recognising the factors that contribute to sustainability, both positively and negatively, and based on well-established theoretical frameworks such as innovation, technology spillover effect, and stakeholder theories, improves theoretical discourse and guides practical actions. This research contributes to existing knowledge on sustainability and informs evidence-based decision-making in the context of the BRI. This study's valuable policy recommendations for BRI partner countries include prioritising investments in ICT infrastructure and digital literacy programs to enhance sustainability outcomes. It emphasises the significance of good governance practices and institutional reforms in fostering development. Adopting sustainable urban planning and management practices is crucial for addressing the challenges associated with rapid urbanisation. This study highlights the significance of investing in R&D in driving sustainability outcomes. It also offers insights into the challenges and opportunities arising from the COVID-19 pandemic and recommendations for alleviating its adverse impact on sustainability in BRI partner countries.

CRediT authorship contribution statement

Saba Khan: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saif Ullah:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haitham Nobanee:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

There is no conflict of interest.

Data availability

Data will be made available on request.

Appendix 1. Results of Time Effect Through the Two-Step System GMM and D-K regression

Dep. Variable	(1) Two-Step System GMM Main Model	(4) D-K regression Robust Model
2013	Base Year	
2014	0.054***	0.0654***
	(0.005)	(0.006)
2015	0.053**	0.0765***
	(0.009)	(0.003)
2016	-0.045	-0.0345
	(0.005)	(0.010)
2017	0.065***	0.0754***
	(0.008)	(0.004)
2018	0.046***	0.0345**
	(0.074)	(0.06)
2019	0.065**	0.068***
	(0.008)	(0.004)
2020	0.076*	0.073**
	(0.003)	(0.004)
2021	0.064**	0.0765**
	(0.004)	(0.007)

Standard errors are in parentheses: *** $p<0.01$ (1%), ** $p<0.05$ (5%), * $p<0.1$ (10%)

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